Current Structure in Elliott Bay, Washington: 1977–1996

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Introduction

This paper describes the average water movement in Elliott Bay located off Seattle, Washington. Averaging over monthly (28-day) intervals effectively filters out the hourly and daily swings of currents associated with tides and winds. This enabled the historical current records to be combined into a conceptual flow pattern for the Bay (Figure 1).

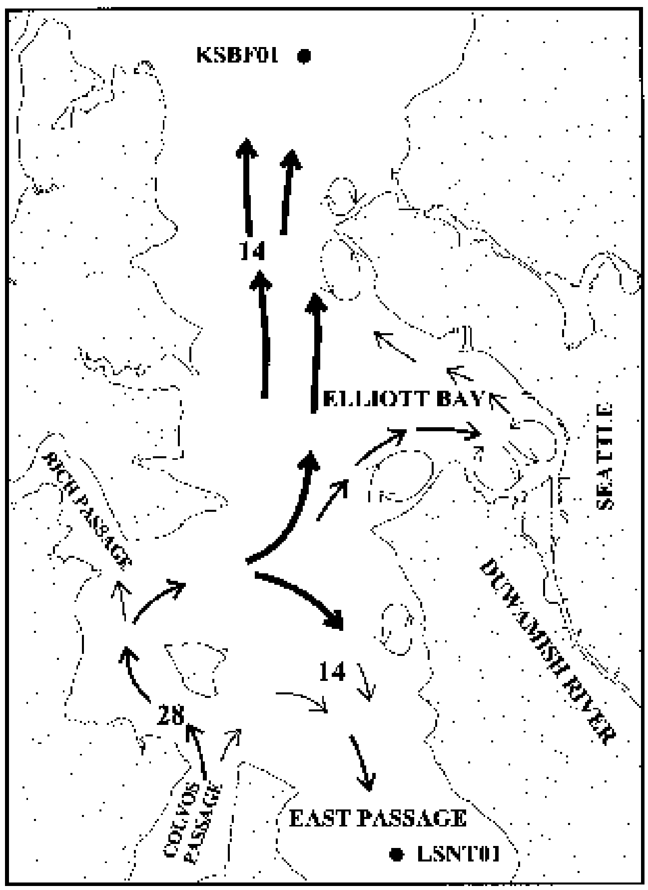

Fig. 1. Conceptual upper-layer flow pattern, Elliott Bay and approaches, ~0–50 meters. See Figure 5 for detailed flow in Elliott Bay. Numbers indicate approximate discharge in 10^3 m^3/sec. The discharge from Colvos Passage (~ 28,000 m^3/sec), largest of all Puget Sound water bodies, splits with approximately half diverging southward into East Passage and half feeding north of Alki Point. Unknown, but small transports (order of 10^3 m^3/sec) are thought to flow through Rich Passage and Elliott Bay. Permanent eddy pairs swirl north and south of Alki and West Points. Data presented in this paper suggest that an eddy pair may exist in Elliott Bay.

Historical data, together with observations of drift cards, water density, and currents made during March–June 1996 were analyzed to aid in siting an outfall from the combined sewer overflow (CSO) located in Myrtle Edwards Park known as the Denny Way CSO. Taking additional oceanographic measurements helped refine the CSO's placement with respect to anchorage and cable areas and other facilities, including the grain terminal and tribal net pens (Figure 2).

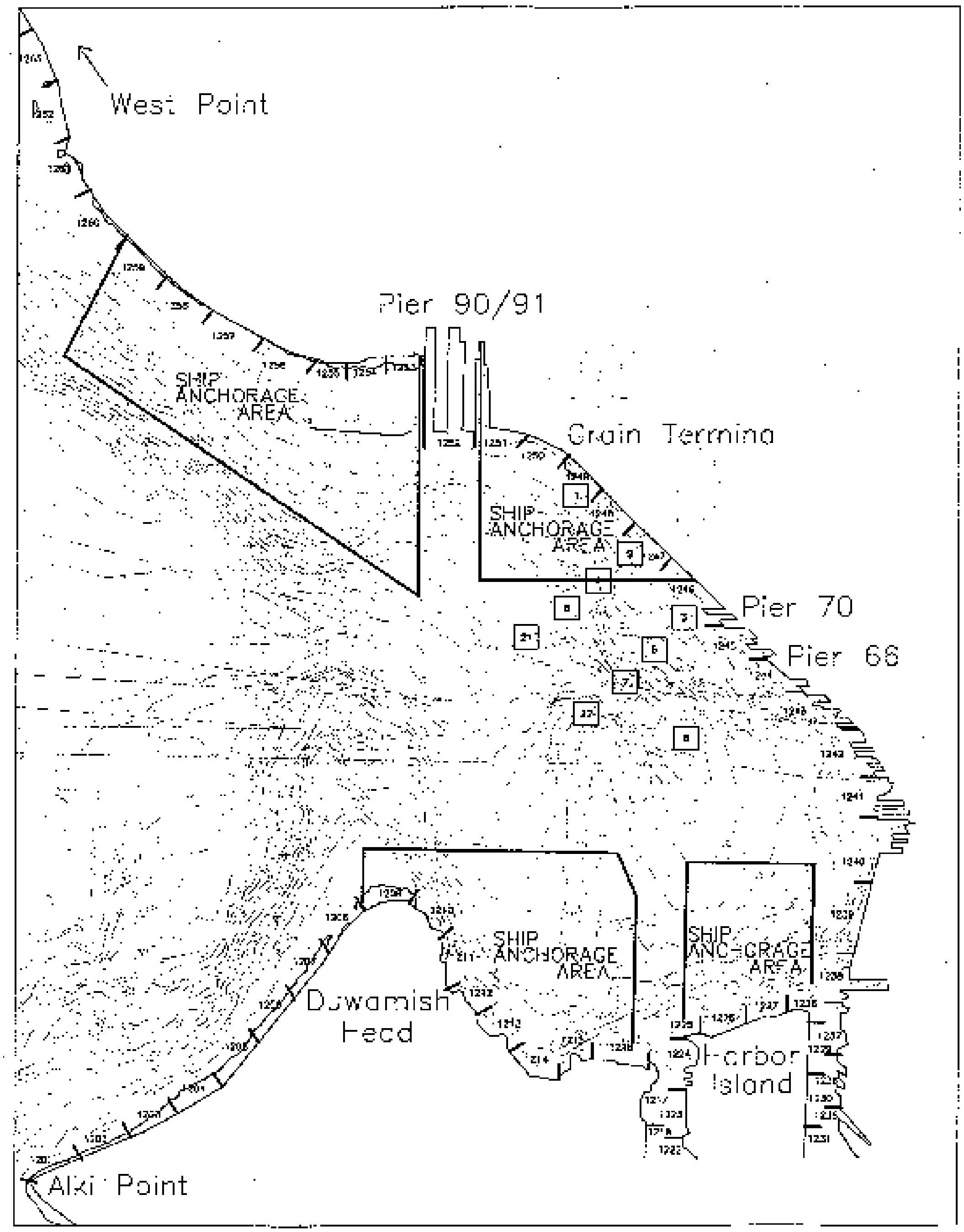

Fig. 2. Drift card release sites (squares) along the north and south transects. Two additional sites (1, 8) lying off the transects were added to obtain greater alongshore coverage. Numbers within squares indicate site designations. Ticks along shore mark 0.25-mile-long shoreline segments between Alki (segment 1201) and West (segment 1267) Points. The Denny Way CSO lies at the inshore end of the south transect (site 3).

The current meter records were partitioned into depth strata containing water arriving from three distinct sources: near-surface layer (0 to ~8 m) containing diluted fresh water from the Duwamish River; mid-depth layer (8–50 m) containing water formed in the Tacoma Narrows and discharged through Colvos Passage; and the deepest layer (50 m to sea floor) containing water formed in Admiralty Inlet.

The movements of floating wooden drift cards, where current meters could not be placed for practical reasons, showed the movement of water nearest the sea surface. To analyze the drift card recoveries three regions were defined with respect to north-south lines drawn between 1) Duwamish Head and the Elliott Bay Marina, and 2) Alki and West Points. Inner Elliott Bay is east of (1), outer Elliott Bay is between (1) and (2), and the Main Channel extends west of (2).

A note regarding units: 3.28 ft = 1 m; 10^3 m = 1 km; and to obtain density expressed in sigma-t units, subtract one from the measured density and multiply by 1,000 (e.g., a density of 1.022 grams per cubic centimeter equals 22 sigma-t units).

Background: Effluent Behavior in Changing Climates

Previous syntheses of historical data provided a net flow diagram for Puget Sound (see Cokelet et al., 1991). Off Seattle near Main Basin's mid-channel, the flow consists of two layers, the upper layer flowing to the north and the lower layer flowing south. Effluent in the 50-m-deep upper layer travels in a few days from Alki Point to Admiralty Inlet, where roughly two-thirds of the estuarine transport exits Puget Sound into Juan de Fuca Strait. The remaining one-third is mostly refluxed downward so as to return to Alki Point in the 150-m-thick lower layer.

Effluent rises from an outfall diffuser and traps at a depth depending on oceanographic parameters and diffuser design. Water parameters include variations of density with depth and current strength in the flow layers. Previous studies indicate that the effluent from the West Point treatment plant rises into the upper layer (from 71 m [233 ft] deep diffuser, to the depth range of 30–50 meters [98–164 ft]), and effluent from the Renton outfall remains submerged in the lower layer [rises from a depth of 200 meters (656 feet) to approximately 100–150 m (328–492 ft)].

Whereas diffuser models provide reliable information on the depth ranges in which the effluent plume is trapped, depth variations of the separation between the upper and lower flow layers remain unexplored, excepting along a cross-channel transect between Meadow Point and Point Monroe (Ebbesmeyer et al., 1984). Although numerous oceanographic parameters fluctuate at decadal periods (e.g., water temperature, current variations with depth; 10 20-year period), the one which primarily determines effluent equilibrium depth—variations of water density with depth—remains reasonably steady as averaged over a year (see Ebbesmeyer et al., 1989).

Because current strength in the Main Basin's flow layers fluctuates with climate regime, the environmental data base was divided into years associated with two climatic patterns: warm and dry (WD); and cold and wet (CW; Ebbesmeyer et al., 1989). During WD intervals river runoff entering Puget Sound was below normal, water temperatures rose above 9.69 $^{-C}$, and currents in the Main Basin deeper layer flowed fastest in the depth range of 160 meters to the sea floor. During the CW intervals runoff increased above normal, water cooled below 9.69 _C, and the deep layer currents flowed fastest near 100 m (see Ebbesmeyer et al., 1989).

CW intervals occurred prior to 1926 since approximately the turn of the century, and during 1946–1977, and WD intervals occurred during 1926–1946, and since 1977 (Ebbesmeyer, et al., 1989; Table 1). To ascertain whether WD conditions persisted through 1996 current meters were deployed at the historical site during the present study and the temperatures measured during King County's monitoring program were examined.

Elliott Bay Historical Current Meter Measurements

Beginning in the late-1970s current meters were deployed in Elliott Bay in support of various environmental studies (Table 2). A single current meter record consists of current speed and direction determined several times per hour. Since the tides repeat roughly at two-week intervals, and nearly all the

Elliott Bay records lasted about a month, to achieve current averages with highest statistical certainty, the records were truncated at two 14-day intervals (i.e., 28 days). All totaled, 229 current meter records, each lasting 28 days, were available for this analysis (Table 2).

Table 1. Annual average temperature (at 150 m) in Puget Sound's Main Basin. Since 1934, water temperatures were measured monthly in the Main Basin in about half the years between 1934 and 1996. The mean values at 150-m depth for 1985–1995 were derived by averaging Metro stations KSBP01 and LSNT01 within individual months, then averaging the observations made January—December. Averages for other years are from Ebbesmeyer et al. (1989).

(a) Cold/Wet (CW) Years		(b) Warm/Dry (WD) Years	
Year	**Annual average temperature (°C) (< 9.69°C)**	**Year**	**Annual average temperature (°C) (≥9.69°C)**
1935	9.39	1934	9.85
1936	9.17	1938	9.69
1937	8.86	1940	10.43
1939	9.57	1941	10.61
1951	9.41	1958–59	10.10
1952	9.34	1977	10.36
1953	9.67	1979	10.11
1954	9.22	1980	10.35
1955	8.77	1981	10.67
1966	9.57	1982	10.01
1968	9.50	1983–84	10.65
1970–71	9.51	1990	9.94
1973	8.99	1991	9.85
1974	9.29	1992	10.34
1975	9.29	1993	9.84
1976	9.13	1994	10.41
1989	9.48	1995	10.61
		1996	9.92
Sample size	17 years		18 years
Mean	9.30 _C		10.21-C
Std. dev.	0.26-C		0.32-C

Table 2. Sources of historical current meter data for Elliott Bay. Abbreviations: CSO, combined sewer overflow; ETS, effluent transfer system; WTP, wastewater treatment plant.

Study name	Date	Observation area	Number of current meter records	Reference
Denny CSO	3–6/96	Northern Elliott Bay	18	This paper
Renton ETS	10/83–8/84	Inner outer southern Elliott Bay	112	URS Engineers and Evans-Hamilton, Inc. (1986)
Alki WTP	5/84–9/84	Alki Point	22	Hermes et al. (1985)
Elliott Bay Waterfront Recontamination Study	10/93–10/94	Piers 48–59	40	WA Dept. Ecology (1995), Michelsen et al. (1998)
Pacific Marine Environmental Laboratory (NOAA)	8/79–3/80	Inner and outer Elliott Bay	20	Silcox et al. (1981)
Army Corps	10/84–1/85	Four Mile Rock	3	Evans-Hamilton, Inc. (unpubl. records)
Army Corps	5/79–9/80	Harbor Island	6	L.H. Larsen (unpublished)
King County	1/97–5/97	Inner and outer Elliott Bay	8	Shuman and Schock (1997)
Total # records			229	

New Oceanographic Data

Oceanographic data collected in 1996 were of three types:

Currents

Current meters were deployed from 15 March through 27 June 1996. Six current meters were deployed comprised of three electromagnetic current meters manufactured by InterOcean Systems (model S4), and three Acoustic Doppler Current Profilers (ADCPs) manufactured by RD Instruments. At the Main Basin reference site (Mooring 25; see Figure 5 for location) five Aanderaa (model RCM4) current meters were tethered from a submerged buoy.

Water profiles

Profiles of temperature, salinity, density and dissolved oxygen versus depth were obtained at 20 sites using a Seabird CTD on 18 March, 29 March, 18 April, 6 May, 20 May, 4 June, and 18 June 1996. Conductivity-temperature-depth (CTD) data from monthly monitoring by King County Department of Natural Resources at stations KSBP01 (located off Point Jefferson) and LSNT01 (located at the northern end of East Passage) were used to compute annual average temperatures for 1985–1996 (Table 1).

Drift cards

Because Duwamish River water is concentrated in the shallowest 8 m of the Bay where it is not cost-effective to deploy current meters, and information was desired regarding floating effluent materials, drift cards were released. Wooden drift cards bob in the upper few inches nearest the sea surface, where oil and grease effluent materials tend to reside (Word et al., 1990). Made of wood and coated with non-toxic paint, the cards were fabricated so as to pose minimal environmental harm. On each CTD cruise, batches of 50 individually numbered cards were released at eight of the CTD sites totaling 2,800 cards (see Figure 2 for locations). This paper describes 1,324 recoveries reported as of 12 July 1996 (47.3% of 2,800 total releases). Stringent project reporting requirements dictated the quick termination date.

Current Patterns in Density Strata

The CTD profiles indicated water strata defined by density gradients (Figure 3). Within the shallowest two density strata net current speed and direction were composited to ascertain the general current patterns. The paucity of records prevented an interpretation of the lower layer current patterns.

The records were combined regardless of season on the hypothesis that the dominant mechanism forcing the Bay above 50 m is the tidally pumped water exiting Colvos Passage (Figure 1; Ebbesmeyer and Barnes, 1980). The monthly average discharge from Colvos Passage tends to be relatively steady over the year (Ebbesmeyer et al., 1984).

Regarding the climate regimes, the first and third deployments at Mooring 25 exhibited current profiles characteristic of WD years, whereas the second deployment was characteristic of CW years (Figure 4). Averaged over the three deployments, the profile resembles that from the WD regime. Furthermore, the annual average temperature at 150 m fell in the range associated with the WD regime (Table 1). Since the most recent WD regime embraces the available current meter records, all of the records shown in Table 2 were utilized in the following interpretations.

Upper Layer (0– ~8 m)

The shallowest layer extends over the depth range of strongest vertical density gradients, or the sea surface to ~8 m. Few instruments have been deployed in this stratum because ship keels often penetrate deep enough to snag moored current meters. This layer is comprised of fresh water from the Duwamish River diluted with Puget Sound water. Because Duwamish River discharge is a small fraction of Puget Sound's total runoff (~1,200 m^3/sec), the shallowest layer is a relatively thin and narrow ribbon of murky water snaking northward along Seattle's waterfront.

Forty current meter records obtained a meter above the sea floor along Seattle's waterfront showed a net convergence centered on the ferry terminal at Pier 52. Ferries idle there for about nine hours per day, generating an average westward discharge equalling 60–75 m^3/sec (Washington State Department of Ecology, 1995; Michelsen et al., 1998). The ferry-induced transport appears sufficient to interrupt the upper-layer flow headed north along Seattle's waterfront.

Intermediate Layer (~8–50 m)

Beneath the Duwamish River plume the intermediate layer consists of water formed by tidal pumping at The Narrows and ejected from Colvos Passage (Figures 1 and 5). Tidal currents flowing around Alki Point form residual eddies north and south of Alki Point (Figure 5). As the northern eddy spins it feeds a portion of the Colvos Passage water into inner Elliott Bay. The intermediate layer, as reflected by the density profiles, extends to the depth of no-net-motion as observed at Mooring 25 (50–80 m; Figure 4).

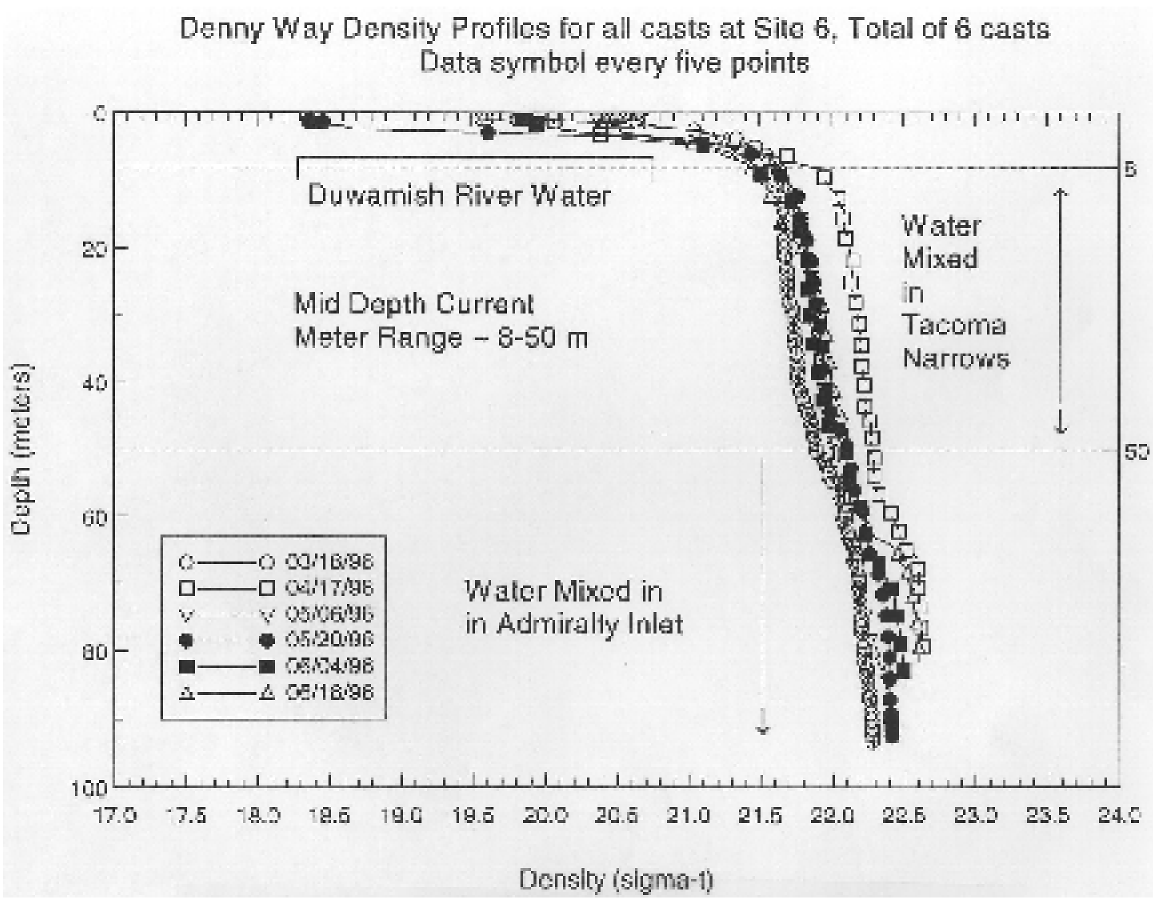

Fig. 3. Flow layers in Elliott Bay derived from density profiles. Six CTD casts made at Site 6 during the drift card releases are shown (see Figure 2 for site location; dates of profiles are shown at lower left). Symbols indicate every fifth data point obtained from the CTD profiles. The near-surface layer, characterized by strong vertical density gradients, contains the discharge from the Duwamish River. The mid-depth range contains water formed at the Tacoma Narrows, whereas water in the deepest layer was formed in Admiralty Inlet.

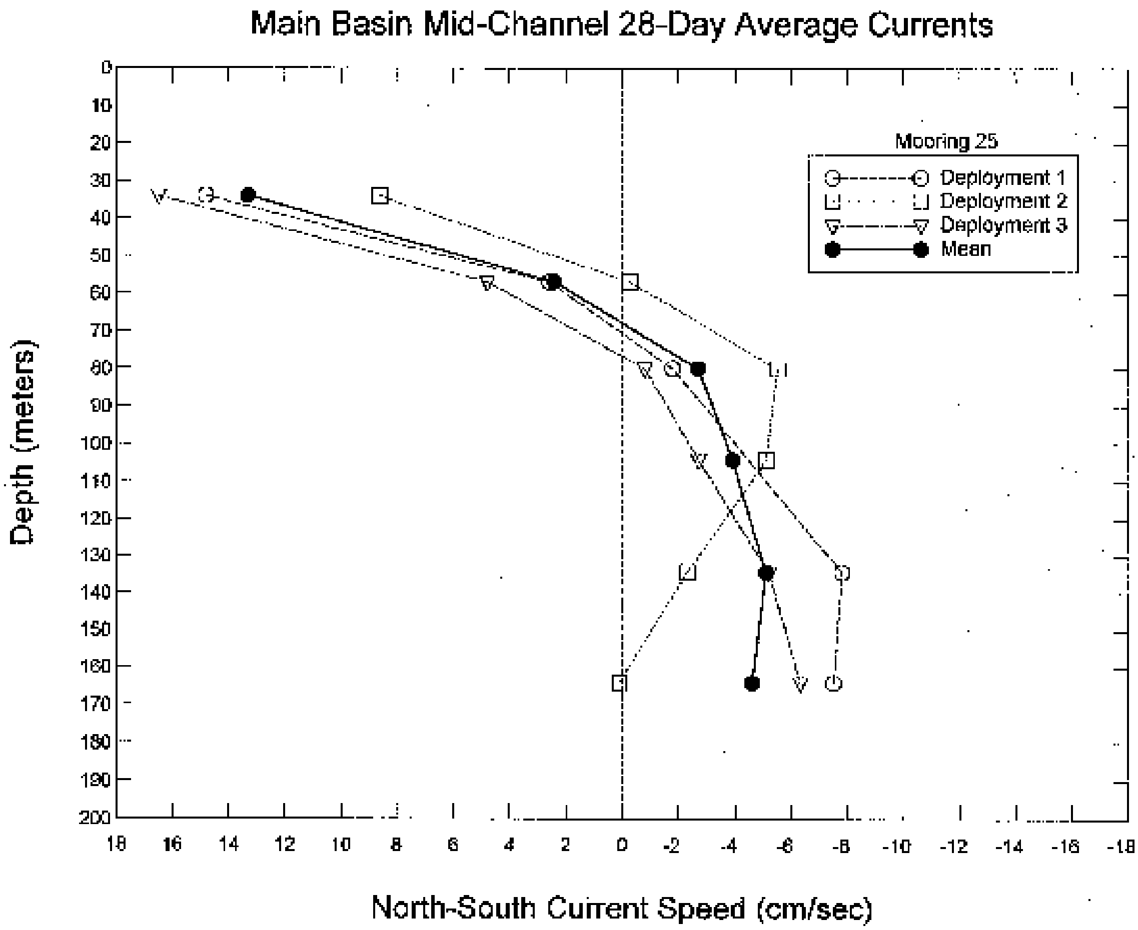

Fig. 4. Profiles of net north-south current speed in the Main Basin at Mooring 25. See Figure 5 for Mooring 25 location. Note that currents head north on the left and south on the right. Net speeds were computed from three, month-long current meter deployments (see code at upper right): deployment 1, 19 March–15 April; deployment 2, 20 April–17 May; and deployment 3, 25 May–21 June. The average of the three deployments is shown by the solid circles. Note that the depth of no-net-motion, corresponding to zero net current speed, varies between 55–75 m with a three-month average equaling 68 meters.

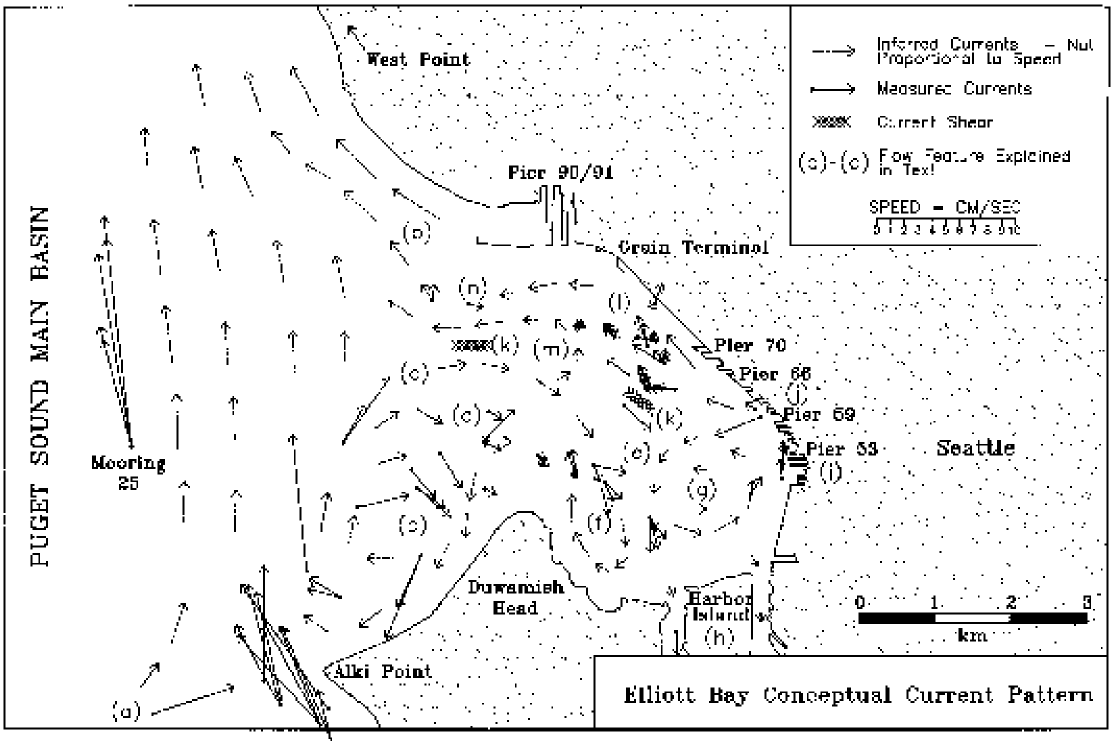

Fig. 5. Conceptual flow pattern, upper 50 meters, Elliott Bay. See text for explanation of codes a–o and box at upper right for codes of the current vectors. The current flow pattern shown in the Seattle Post-Intelligencer published on 23 April 1997 (Thursday morning edition; George, 1997) was adapted from this illustration. See Figure 1 for the broader context of this circulation pattern.

Combined Layers (0–50 m)

The elements comprising the Bay's flow pattern are (*a–o* shown in Figure 5; see also Figure 1):

***a. Colvos Passage*.** At the northern end of Colvos Passage, half the flow diverges southward into East Passage, and half continues northward to Admiralty Inlet with a small fraction feeding into Elliott Bay. The refluxing model of Puget Sound indicates a net volume transport equaling 14,000 m^3/sec flowing past West Point (Cokelet, et al., 1991), and the hydrodynamic model of Liou (1991) suggests that 1,000 m^3/sec of the Colvos Passage efflux passes though Elliott Bay (i.e., ~4% of the Colvos Passage discharge).

***b, c, d. Eddy North of Alki Point*.** During ebb tides, as water at mid-channel travels northward, an eddy develops in the lee of Alki Point. Because this eddy develops twice daily during major ebb tides, it influences currents averaged over long periods of time. Some of the water circulating in the Alki eddy diverges northward at *(c)*, and a portion spins around Duwamish Head into inner Elliott Bay at *(d)*.

***e, f, g. Eddies of Inner Bay*.** Water diverging from the Alki Point eddy at (*d*) initially flows into Elliott Bay through the submarine canyon. As the water exits the canyon and enters inner Elliott Bay, the expanding flow may generate eddies, one to the north at (*m*) and the second in the southern portion of inner Elliott Bay. This flow may divide at (*e*) into eddies centered over the submarine canyons at *(f)* and *(g)*.

h. Inflow to the Duwamish River. At the southern terminus of inner Elliott Bay, small amounts of marine water are drawn southward into the estuarine flows within the waterways west and east of Harbor Island. Current measurements made approximately one meter above bottom indicate net southward speeds of approximately 1 cm/sec in the waterways (Kurrus and Ebbesmeyer, 1995).

i, j. Flow Along Seattle's Waterfront. A northward flow occurs along the Seattle waterfront, with two exceptions: the discharge from idling ferries may also influence flow in the intermediate as well as the upper layer; and near (j) the large net current directed westward may result from an anomaly in the seafloor bathymetry.

k, l, m, n. Flow Exiting Inner Bay. North of the submarine canyon the flow is directed westward. The hatched areas at *(k)* indicate currents separating the juxtaposed inflowing and outflowing waters. A portion of the inflowing water recirculates into the outflow at *(m)*. At *(n)* the outflow generally follows the bottom contours.

o. Outer Bay Flow. Water in the shallowest two layers exiting outer Elliott Bay merges with the Main Basin's upper layer.

Drift Cards

To quantify the drift card recoveries, the Bay's shoreline was segmented into 67 0.25-mile-long intervals (Figure 2). Nearly all of the cards recovered were found downstream (segments northwest of the drops) of the release sites, compared with a few percent in the upstream (segments southeast of the drops).

The fraction of drift cards recovered within the inner Bay was tabulated as a function of distance they were released offshore (Figure 6). Along the north transect, the recoveries decrease three-fold within 1,300 feet from shore. Between 1,300–3,800 ft offshore, the recoveries decrease from 30% to 15%. Of the 75% change that occurred within 3,800 ft, three-quarters occurred within the first 1,300 ft. Along the south transect, the percentage recoveries decreased after first increasing. The offshore maximum remains unexplained.

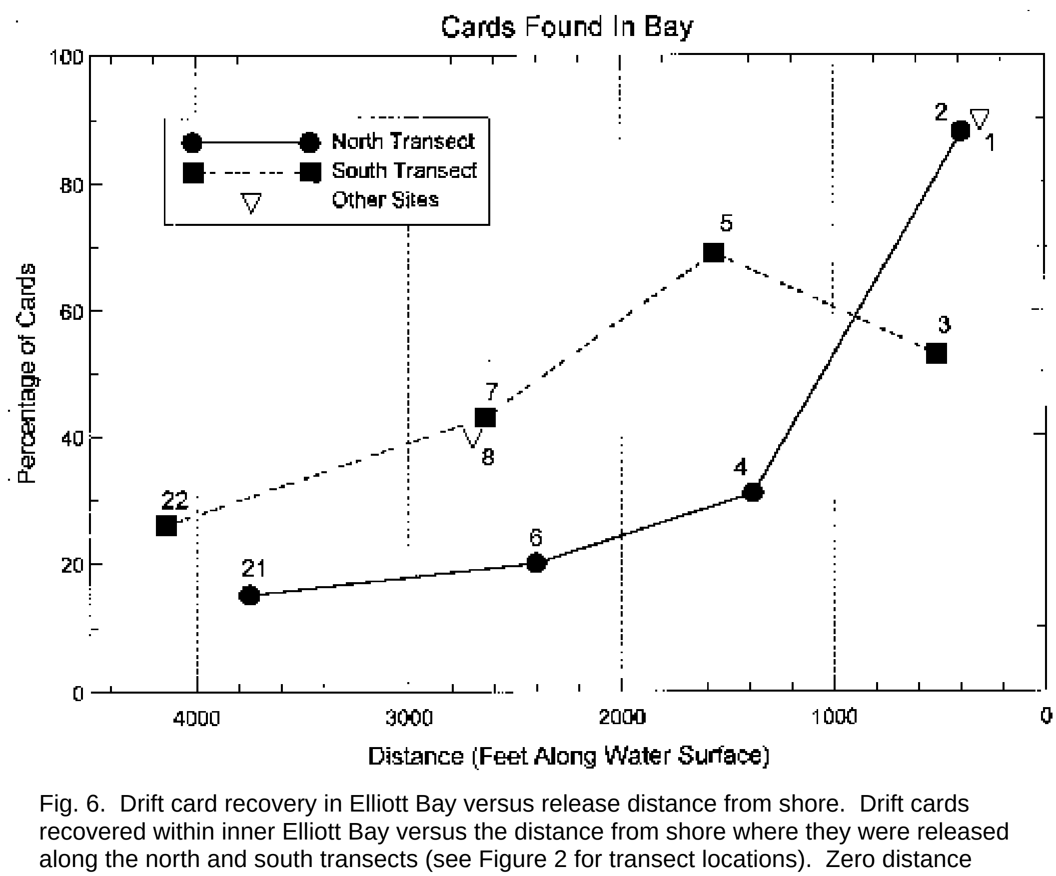

Fig. 6. Drift card recovery in Elliott Bay versus release distance from shore. Drift cards recovered within inner Elliott Bay versus the distance from shore where they were released along the north and south transects (see Figure 2 for transect locations). Zero distance corresponds to Mean Lower Low Water, and numbers indicate the drift card release locations shown in Figure 2.

Historical oceanographic observations indicate that along a given shoreline, floatable debris collects in localized segments. Realizing this, on a single occasion, investigators walked the shoreline from Alki to West Points searching for drift cards. Four shoreline segments accounted for 82% of the recoveries in the vicinity of the following facilities: Denny Way CSO, the pocket beach in Myrtle Edwards Park, the net pen fish farm in the vicinity of the grain terminal, and the Elliott Bay Park and fishing pier. All totaled, 93.4% of the cards recovered in Elliott Bay were found in 15 of the 67 segments. In other words, nine-tenths of the cards were recovered in one-fifth of the shoreline.

The 1,324 recoveries were tabulated in 16 regions of Puget Sound and Juan de Fuca Strait (Table 3; Figure 7). Overall, the recoveries reflect prevailing surface current patterns. Half occurred in inner Elliott Bay (Region 10) because of the proximity of the sites to the Bay's shore (Table 3). The next highest percentage (17.4% in Region 7) occurred between West Point and Admiralty Inlet because the cards tend to follow the near-shore currents exiting Elliott Bay around West Point. A few cards (3.8%) traveled south in East Passage. The cards that traveled beyond Admiralty Inlet were recovered on well-known collection shores of eastern Juan de Fuca Strait, including Dungeness Spit, Washington, and near Victoria, British Columbia.

Table 3. Drift cards released in Elliott Bay and reported in Puget Sound, and Juan De Fuca Strait. The numbers of cards recovered and the associated percentages of the total reports (1,324) are tabulated. All totaled 2,800 cards were released during three months (18 March–18 June 1996) of which 47.3% were reported by 12 July 1996. For maps of the drift card release sites and the recoveries superposed on the recovery regions, see Figures 2 and 7, respectively.

		Drift cards reported	
Recovery region (Fig. 7)	**General location**	**No.**	**%**
1	Pacific Coast	0	0
2	Western Juan de Fuca Strait	2	0.15
3	Eastern Juan de Fuca Strait	36	2.72
4	Georgia Strait	0	0
5	Admiralty Inlet	63	4.76
6	Whidbey Basin	29	2.19
7	West Point to Admiralty Inlet	230	17.37
8	Due west of Outer Elliott Bay	105	7.93
9	Outer Elliott Bay	70	5.29
10	Inner Elliott Bay	670	50.60
11	Exit area from Colvos Passage	51	3.85
12	East Passage	50	3.78
13	Colvos Passage	1	0.08
14	Southern Puget Sound	0	0
15	Rich Passage	17	1.28
16	Hood Canal	0	0
Total reported		1,324	100.00%

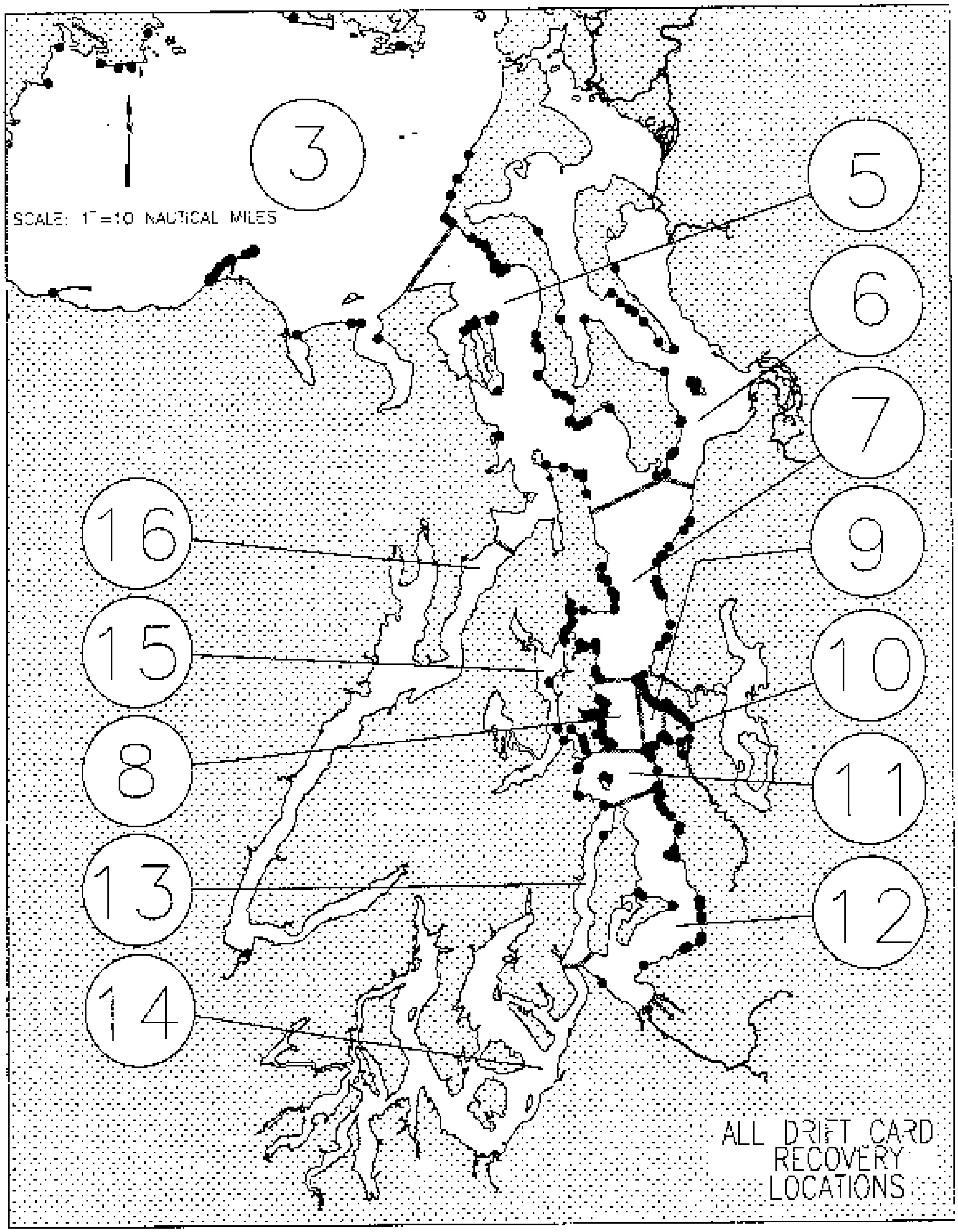

Fig. 7. Recoveries of Elliott Bay drift cards in Puget Sound and Juan de Fuca Strait. Region 1 includes the Pacific coast and region 2 is the western Juan de Fuca Strait adjoining region 3. See Table 3 for tallies of cards found within each division.

Discussion

Despite the accumulation of 229 current meter records at a cost exceeding $1 million, Elliott Bay's flow field remains unresolved to a substantial degree, particularly in the layers shallower than 8 m and deeper than 50 m. The southern portion of inner Elliott Bay may contain an eddy pair, which may be a significant factor in determining the flushing of inner Elliott Bay.

The available historical data suggest a persistent circulation through inner and outer Elliott Bay. What drives the persistent flow? We believe it originates in Colvos Passage because of tidal pumping at The Narrows. Water drawn from East Passage into The Narrows on a flood tide is, with an admixture of Southern Puget Sound water, expelled on the following ebb into Colvos Passage. Monthly averages of the tidally pumped discharge in Colvos Passage shows that it fluctuates less than approximately 10% through the year (Ebbesmeyer et al., 1984). Of the approximately 28,000 m^3/sec discharge exiting Colvos Passage, approximately half continues northward mostly bypassing Elliott Bay, and half refluxes south into East Passage (Figure 1). The present synthesis suggests that a small portion of the Colvos Passage discharge persistently circulates through Elliott Bay.

Within 24 days after the last drift card was released (18 June 1996) the public had reported 47.3% of the total deployed (2,800). The only other sizeable release of drifters in Puget Sound was recently made in Southern Puget Sound involving 9,950 cards deployed inland of Dana Passage during October 1996–September 1997 (Ebbesmeyer, et al., 1998). Within five months the public reported 51.3% of those releases.

The foregoing percentages suggest that there is about a 50% chance of the public reporting a marked drifter floating in the main stem of Puget Sound south of Admiralty Inlet. North of Admiralty Inlet in Juan de Fuca Strait, the percentage recovery decreases by half, based on three previous compilations: 26% of 20,000 historical drifters released throughout Juan de Fuca Strait (Ebbesmeyer et al., 1995); 21.3% of 13,800 drift cards released along the Strait's central axis during January–March 1992 (Ebbesmeyer et al, 1995); and 24.1% of 1,000 cards released off Victoria during June–July 1997 (Crone et al., 1998).

The two-fold difference in recovery percentage between the Sound and the Strait stems in part from the greater numbers lost to the Pacific Ocean from Juan de Fuca Strait than from Puget Sound. The lower population density in the Strait may be contributing factor. Nevertheless, a large fraction of marked floating drifters wash up within the proximity of the public walking the shores of Puget Sound.

Acknowledgements

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